Sensitivity to new high-mass particles decaying to $t\bar{t}$ in fully boosted regime at a 100 TeV collider

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Next steps in the Energy Frontier - Hadron Colliders
25-28 August 2014
Fermilab

100 TeV collider & BSM models with top decays

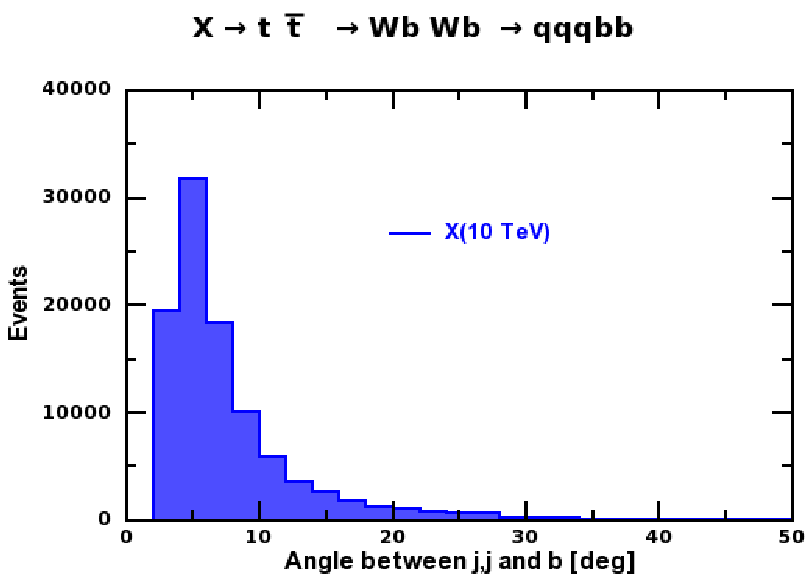
- 100 TeV collider can study physics beyond 10 TeV
- Many BSM models predict decays of heavy particles to $t\bar{t}$
  - top is heaviest known particle!
  - decays to “golden" channels (leptons, photons) can be suppressed
- Heavy means ~10 TeV mass range
- Such masses lead to highly boosted top decays pT(t) > 2-3 TeV

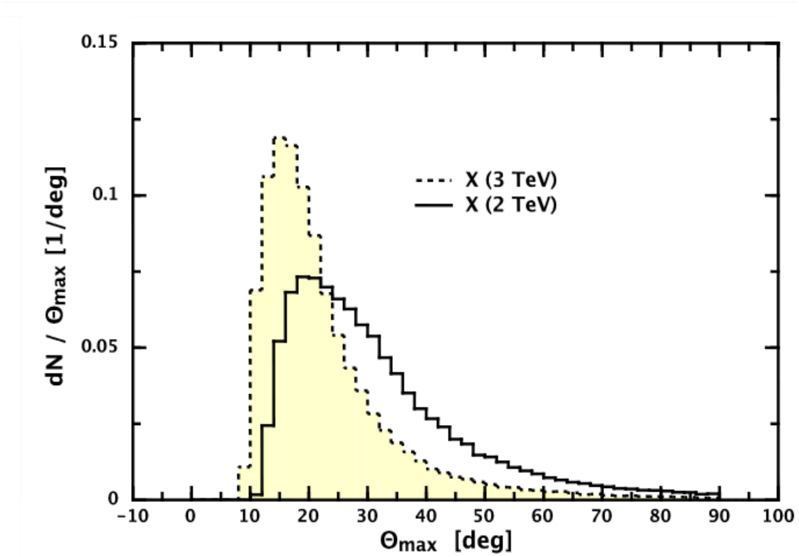
Questions:

- How to measure $t\bar{t}$ resonances at the 10 TeV mass scale?:
  - separate decay particles cannot be “resolved”
  - “traditional” calorimetry
- What are sensitivity limits for a “generic” $t\bar{t}$ resonance using boosted techniques?

Separation of top decay products for X (10 TeV)→ $t\bar{t}$

Phys. Rev. D81 (2010) 114038 S.C. J.Proudfoot





- For ~10 TeV object, typical opening angle between q, $\bar{q}$ and b from t ($\bar{t}$) is 5 degree
- "Highly boosted" regime: decay products are inside "standard" jets with R=0.5
- Event kinematics → "back-to-back" jets
  - top decays form a narrow "core"
  - large final-state gluon radiation introduces extra smearing (Snowmass13, arXiv:1307.6908)

Current landscape of experimental searches

- **8 TeV: ATLAS & CMS** (CERN-PH-EP-2013-032, Phys.Rev.Lett. 111 (2013) 211804)
  - ATLAS:
    - A narrow leptophobic (narrow) Z' is excluded for M<1.7 TeV
    - KK excitation is excluded up to M=2.1 TeV
    - Upper limits: 0.03 pb up to 3 TeV
  - CMS:
    - Z' is excluded up to 2 TeV
    - KK excitation up to 2.5 TeV
  - → Methods: lepton+jets channel:
    - resolved+ some boosted technique (HepTopTagger)

see James Pilcher's talk

- **14 TeV** for pp with 3000 fb^{-1} (Snowmass13, K.Agashe et al, arXiv:1309.7847)
  - Masses < 4-5 TeV can be excluded (depends on reconstruction scenario)

- Region with M(X)>5 TeV is new territory for such searches
- Lepton+jets reconstruction will be very difficult due to large overlap of decay products (especially for e+/e-)

Goals and analysis plan for 100 TeV collider studies

- **Exploring the unexplored. Look at ~10-20 TeV mass range**
- **Using MC simulations, set model-independent sensitivity limits for observation of a "generic" $t\bar{t}$ resonance assuming 100 fb^{-1}**
- **Use Z' and g_{KK} simulations as examples of expected "signal"**
  - Z' is narrow ($\Gamma/M \sim 3\%$) while g_{KK} is broad ($\Gamma/M \sim 16\%$)
- **Use basic substructure techniques to deal with background**
  - irreducible $t\bar{t}$ background
  - QCD dijet background
- **Use a b-tagging with reasonable assumption on efficiency and fake rates**
- **No detector simulation**
  - Our limits are for the best-possible scenarios for $X \rightarrow t\bar{t}$ reconstruction
  - Be careful in extracting limits on the production of Z'/g_{KK}
    - Leptonic decays may have better chances for detection!
    - See, for example D.Hayden, R.Brock, C.Willis (2013) arXiv:1308.5874

MC simulation (I)

- **Signal (LO QCD). PYTHIA8**
  - $f\bar{f} \rightarrow Z0'$ with M=8,10,12,14,16,18,20 TeV. Code 3001. Pure Z' contribution. Γ/M=3%
    - cross section scaled by the k-factor 1.3 (careful here → using 8 TeV CM energy!)
  - $q\bar{q} \rightarrow g_{KK}$ with M=8,10,12,14,16,18,20 TeV. Code 5006. Pure g_{KK} contribution. Γ/M=16%
    - cross section is at LO

- **Background processes:**
  - PYTHIA8 for QCD backgrounds
    - NLOjet++ (NLO) to extract the k-factor (MSTW2008nlo68cl for PDF)
  - HERWIG++ x k-factor as alternative (contain W/Z brem. events)
  - SM $t\bar{t}$ process was generated with Madgraph (MSTW2008nlo68cl for PDF)
    - NLO QCD+ HERWIG6
  - PYTHIA8 for all SM boson processes (like Z/W+jets)
    - Not too realistic, but the usage of “realistic” ALPGEN should not change conclusions

MC simulation (II)

- **Monte Carlo samples from the HepSim Monte Carlo repository:**
  - http://atlaswww.hep.anl.gov/hepsim/
  - Select p → ← p then 100 TeV

hep-ph > arXiv:1403.1886

MC event samples:

- qcd_herwigpp_pt2700
- qcd_pythia8_pt2700
- ttbar_pythia8_pt2700
- pythia10tev_wjet2700
- ttbar_pt2500_mg5
- ttbar_pt2500_mg5_lo
- zprime*_pythia8
- kkgluon_ttbar*_pythia8

Show all

p →← p
7 TeV
8 TeV
13 TeV
14 TeV
33 TeV
100 TeV

e →← e
500 GeV

e →← p
920 GeV

HepSim

Repository with predictions for HEP experiments

Selected: pp collisions, 100000 GeV energy, all type

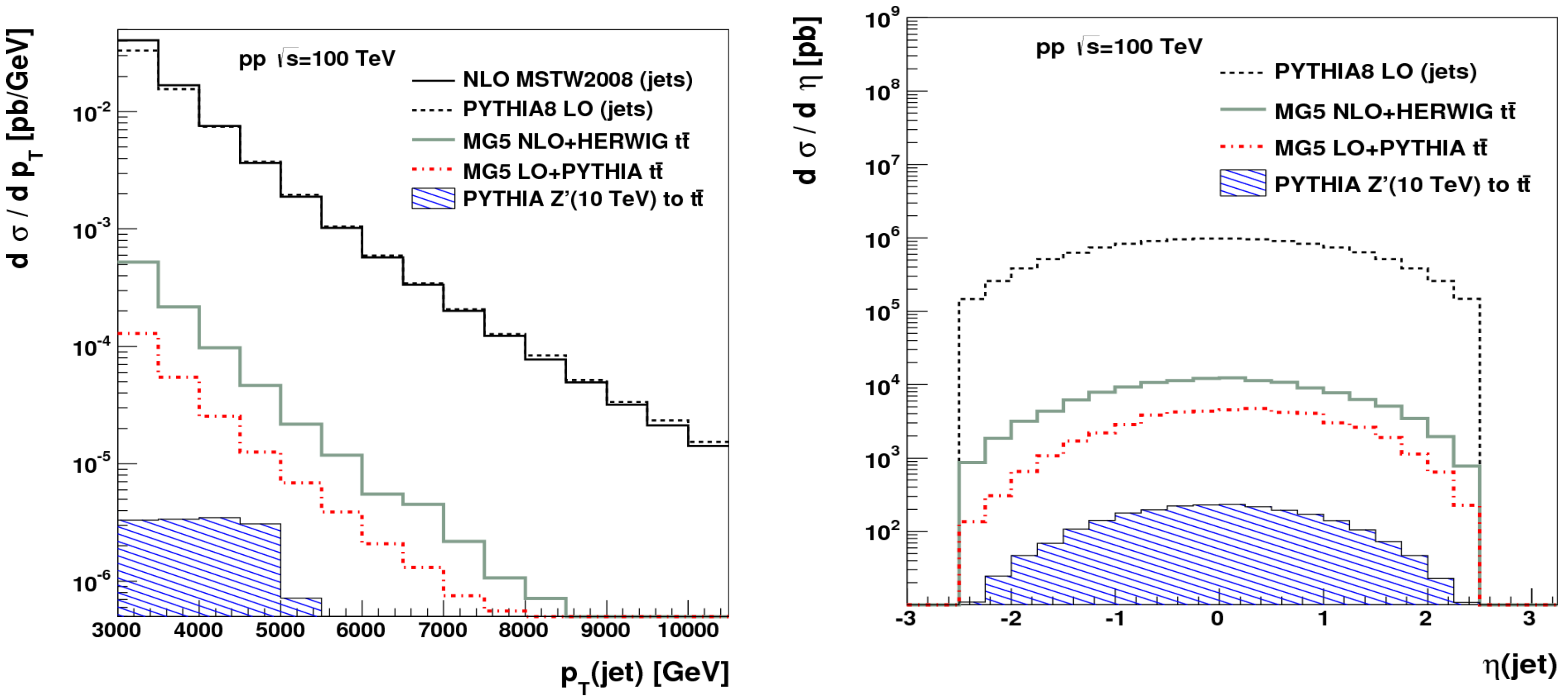
This is a new HepSim database. For more datasets use the Old HepSim repository

Show 25 entries   Previous 1 2 Next   Search:

Id	→←	E (GeV)	Name	Generator	Process	Topic	Info	Url
1	pp	100000.0	higgs_pythia8_100tev	PYTHIA8	gg2Httbar and qqbar2Httbar	Higgs	Info	URL link
2	pp	100000.0	higgs_ttbar_mg5	MADGRAPH+HERWIG6	Higgs+ttbar (NLO+PS)	Higgs	Info	URL link
3	pp	100000.0	kkgluon_ttbar_1tev_pythia8	PYTHIA8	KKgluon (1 TeV) to ttbar	Exotic	Info	URL link
4	pp	100000.0	kkgluon_ttbar_4tev_pythia8	PYTHIA8	KKgluon (4 TeV) to ttbar	Exotic	Info	URL link
7	pp	100000.0	qcd_herwigpp_pt2700	HERWIG++	All dijet QCD events	SM	Info	URL link
8	pp	100000.0	kkgluon_ttbar_8tev_pythia8	PYTHIA8	KKgluon(8 TeV) to ttbar	Exotic	Info	URL link
9	pp	100000.0	kkgluon_ttbar_16tev_pythia8	PYTHIA8	KKgluon (16 TeV) to ttbar	Exotic	Info	URL link
10	pp	100000.0	kkgluon_ttbar_20tev_pythia8	PYTHIA8	KKgluon (20 TeV) to ttbar	Exotic	Info	URL link
11	pp	100000.0	qcd_pythia8_pt300	PYTHIA8	All dijet QCD events	SM	Info	URL link
12	pp	100000.0	qcd_pythia8_pt900	PYTHIA8	All dijet QCD events	SM	Info	URL link
13	pp	100000.0	qcd_pythia8_pt2700	PYTHIA8	All dijet QCD events	SM	Info	URL link
14	pp	100000.0	qcd_pythia8_pt8000	PYTHIA8	All dijet QCD events	SM	Info	URL link
15	pp	100000.0	ttbar_mg5	MADGRAPH+HERWIG6	p p > t t~ [QCD] (ttbar at NLO)	Top	Info	URL link
16	pp	100000.0	ttbar_pt2500_mg5_lo	MADGRAPH+HERWIG6	p p > t t~ (ttbar at LO)	Top	Info	URL link
20	pp	100000.0	ttbar_pythia8_pt900	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
21	pp	100000.0	ttbar_pythia8_pt300	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
22	pp	100000.0	ttbar_pythia8_pt2700	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
23	pp	100000.0	ttbar_pythia8_pt8000	PYTHIA8	g g -> t tbar, q qbar -> t tbar	Top	Info	URL link
24	pp	100000.0	ttbar_mcfm_100tev	MCFM	ttbar production at NLO	Top	Info	URL link

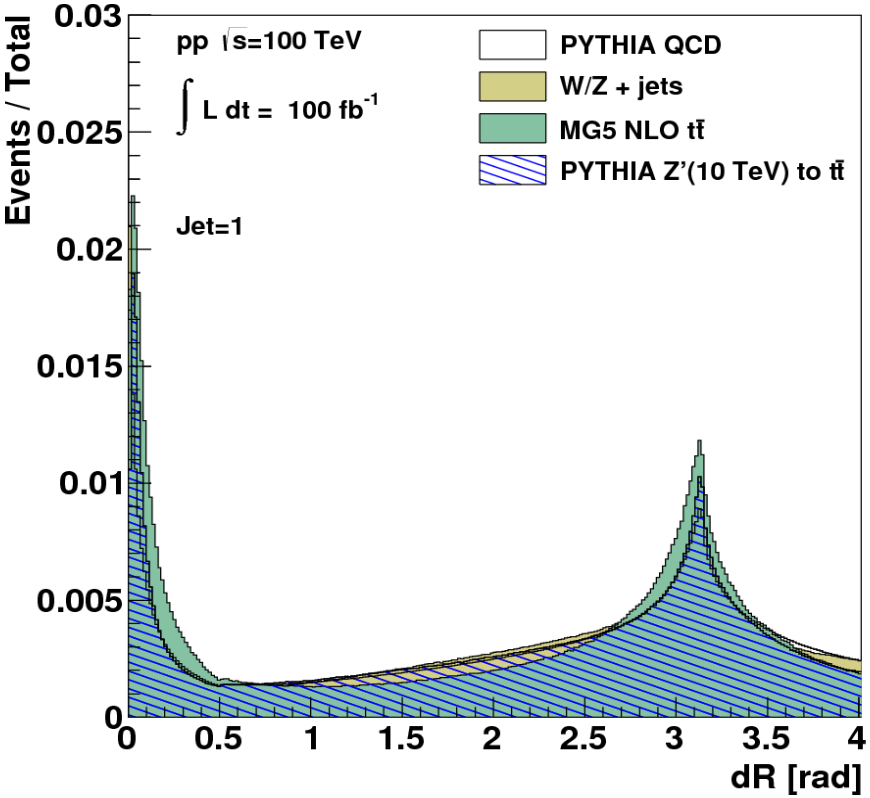
Data samples & analysis program are public

Kinematic distributions



- Jets reconstructed using antiKT5 (R=0.5) from FastJet
- pT(jet)>2.7 TeV and |eta|<2.5
- The k-factor for dijets is ~10%, but larger for $t\bar{t}$
- The distributions look as expected, with a harder pT spectrum for Z'(10 TeV)

Particle distribution inside jets

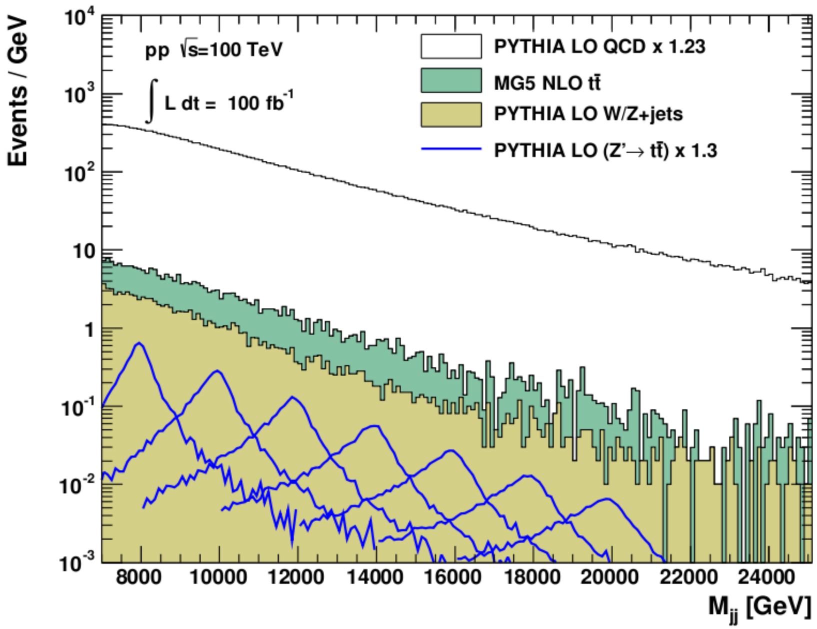


- dR – distance in φ and η between any final state particle and jet center for leading jets

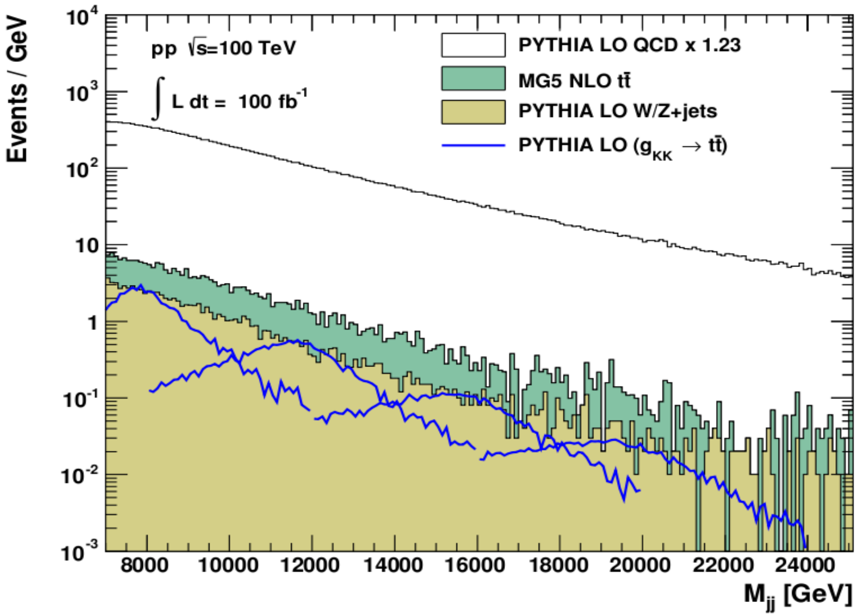
- $t\bar{t}$ jets are broader than jets from light-flavor dijets ("QCD")
- Also broader than $t\bar{t}$ from Z' (harder momentum spectrum)
- For all processes, jet size (R=0.5) is adequate

Dijet invariant mass for 100 fb^{-1}

$Z' \rightarrow t\bar{t}$



$g_{KK} \rightarrow t\bar{t}$



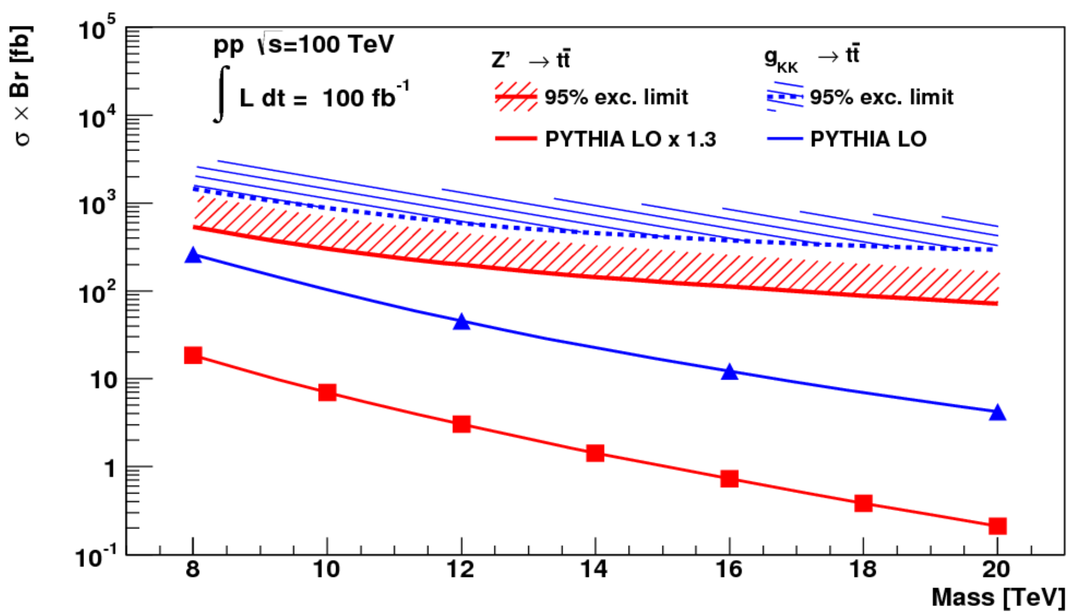
- Look at 2 leading jets above pT>2.7 TeV.
  - all decay channels. Semileptonic decays are included
- Z' model leads to narrow signal ($\Gamma/M \sim 3\%$)
- g_{KK} is wider ($\Gamma/M \sim 16\%$) and has larger cross section

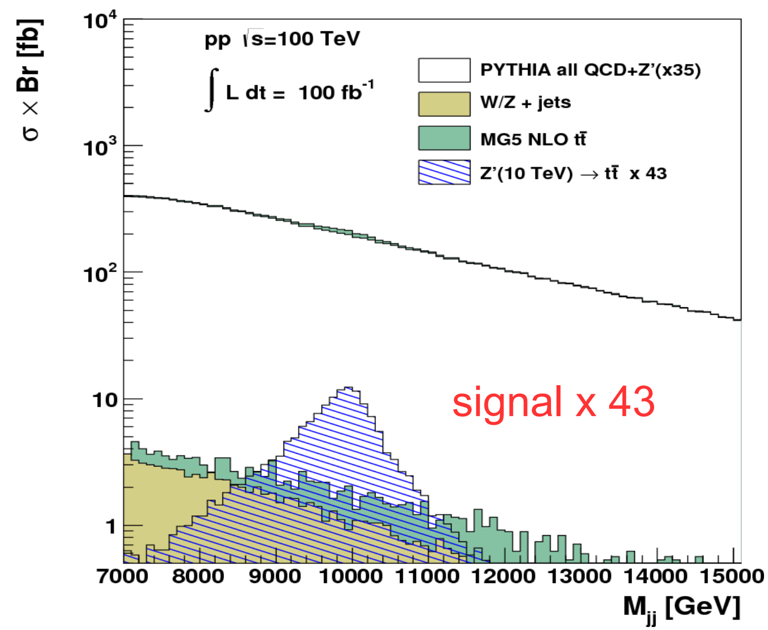
Signal(Z')/Bkg ~ 0.001

Not That Obvious:
How to reduce QCD (reducible) and $t\bar{t}$ (irreducible) background for back-to-back jet events?

Sensitivity limits (no cuts)

Example: Scale Z' cross section scaled until we see it with 95% confidence





Using CL_b method with treatment of statistical uncertainties

Lower limits at 95% C.L. are far away from predicted cross sections

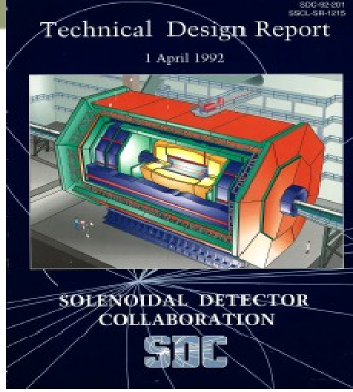
→ g_{KK} cross sections are at LO

→ assume 1.3 correction for Z'

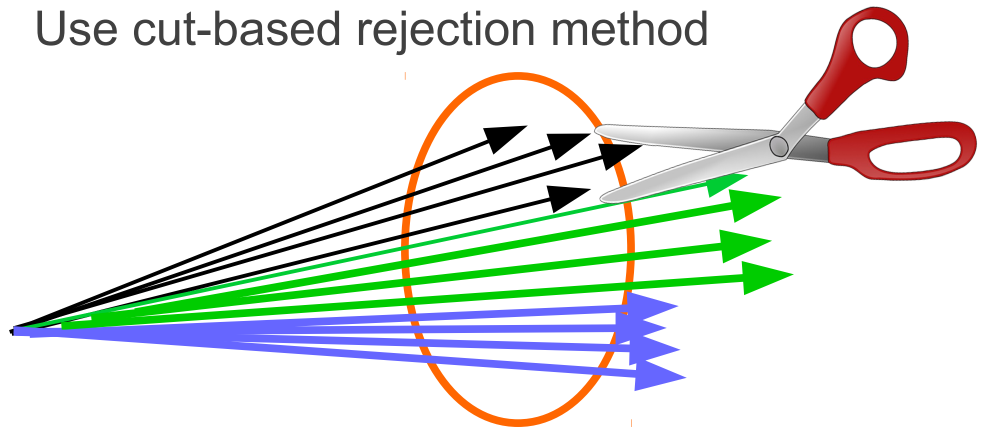
→ NLO corrections can be large ⟶

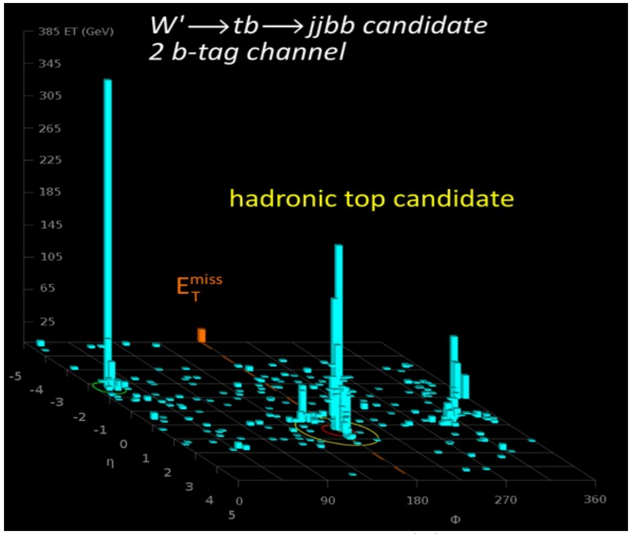
Jun Gao, Chong Sheng Li, Bo Hua Li, Hua Xing Zhu, and C.-P. Yuan, **Phys. Rev. D 82, 014020**

Discriminating variables



- Use jet substructure signatures (SSC-SR-1217 TDR 1992 p 3-26)
- Tremendous recent progress in advancing such approach
- Most basic variables used in this study: (see talk by Brock Tweedie)
  - Jet mass
  - τ_{32} and τ_{21} (N-subjettiness jet characteristics) — J.Thaler, K. Van Tilburg, JHEP 1103:015, 2011
  - Jet shapes (eccentricity) — S.C., J.Proudfoot, Phys. Rev. D81 (2010) 114038
  - $\sqrt{d_{12}}$ splitting scale — J. M. Butterworth, B. E. Cox, and J. R. Forshaw, Phys. Rev. D65 (2002) 96014
  - R^{eff} effective jet radius (weighted with energy radial distance to jet center)
  - b-tagging assuming ~70 efficiency
  - high-pT muons
- Use cut-based rejection method

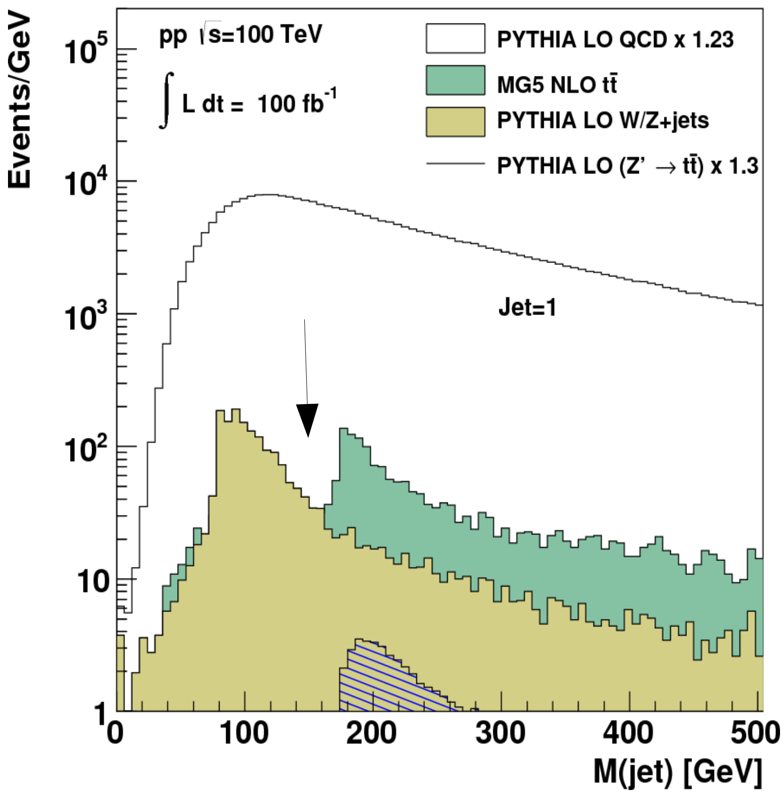


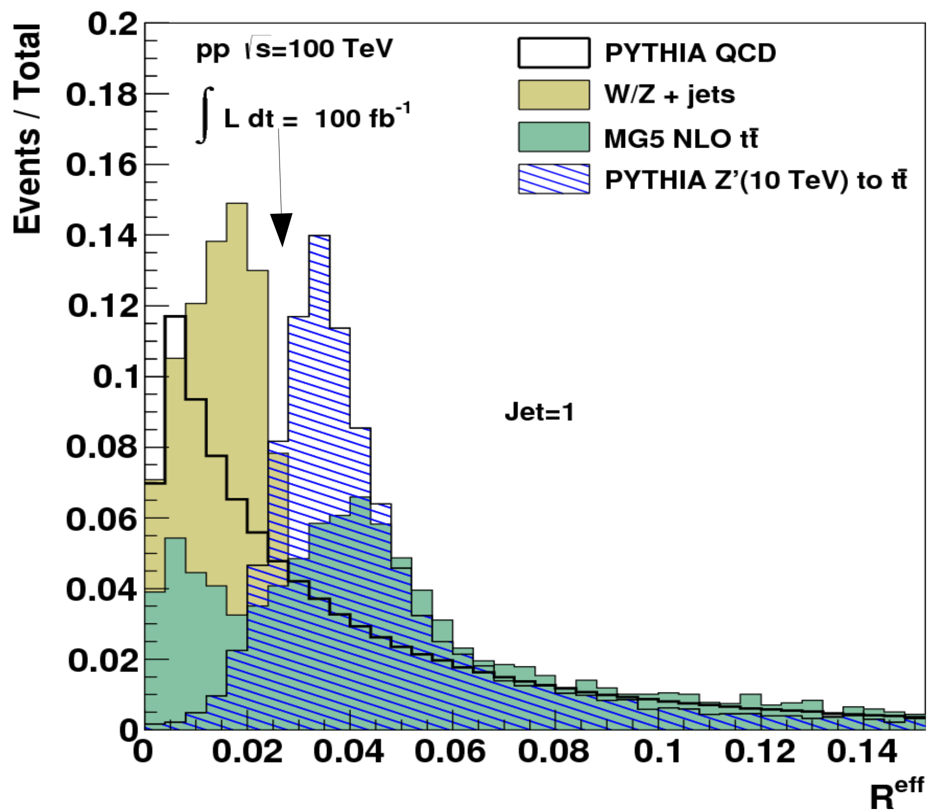


Jet mass & effective jet radius

Example of possible cuts:

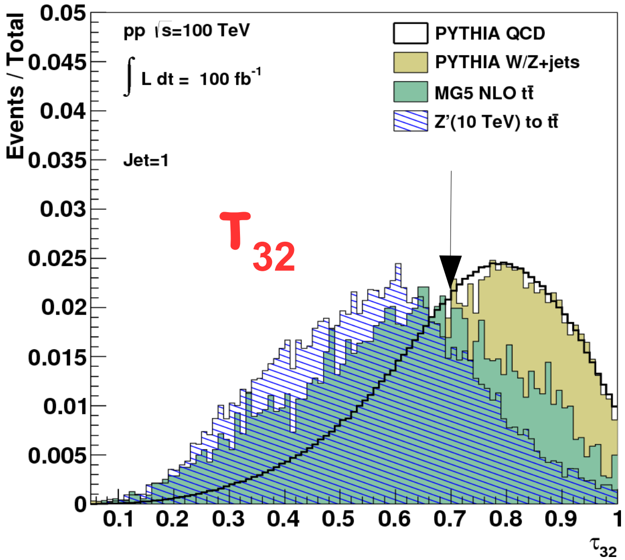
- Look at jet mass of a leading in pT jet. M(jet)>140 GeV rejects:
  - boosted W/Z(+jets)
  - low mass QCD events below the Sudakov mass peak
- Effective jet radius is larger for top-initiated jets

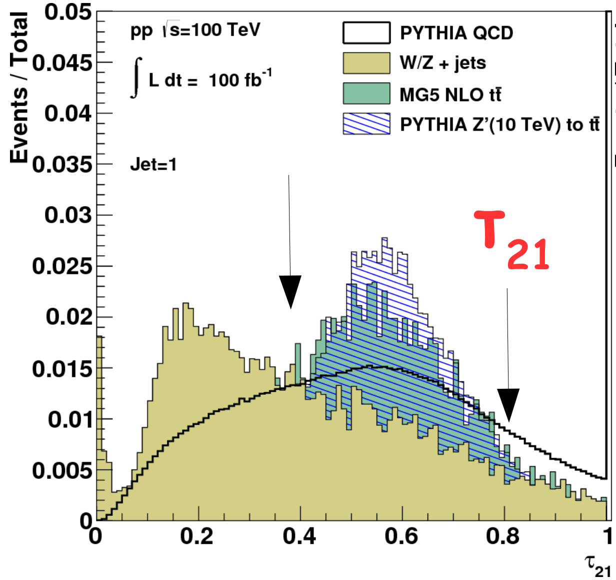


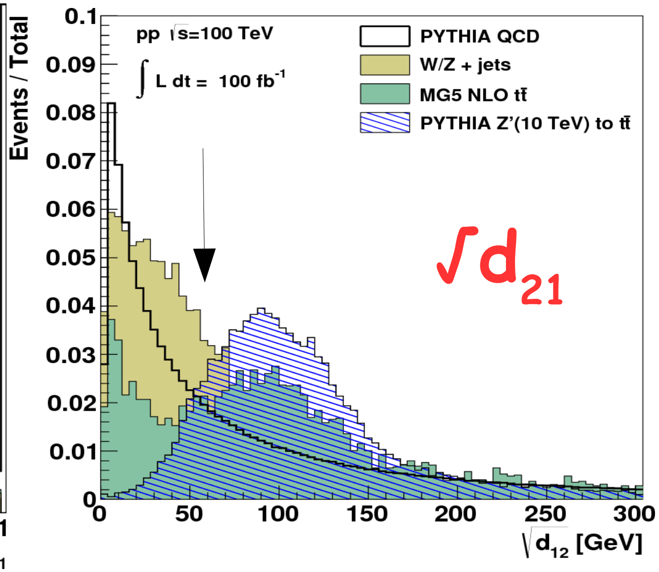


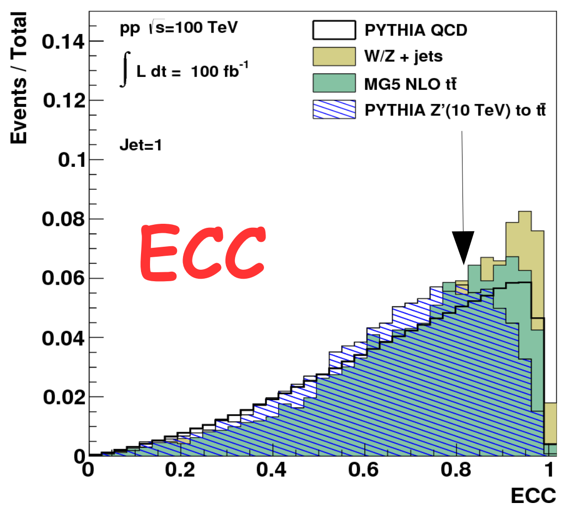
Heavy particles decaying to tt̄ at a 100 TeV collider. S.Chekanov et. al (ANL)

Discriminating variables (lead. jet)





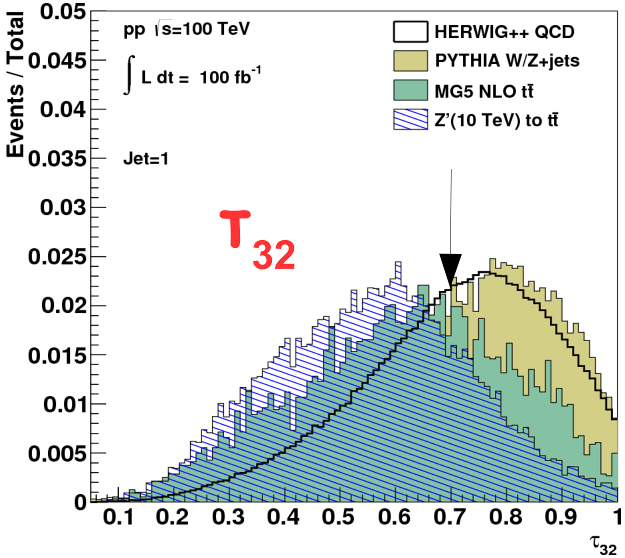


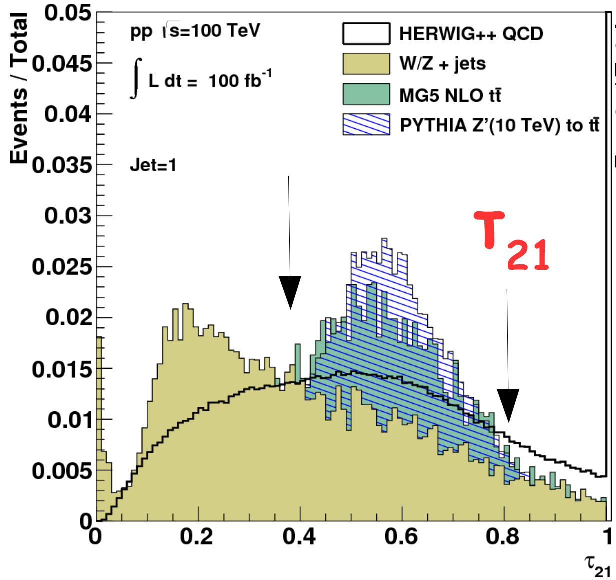


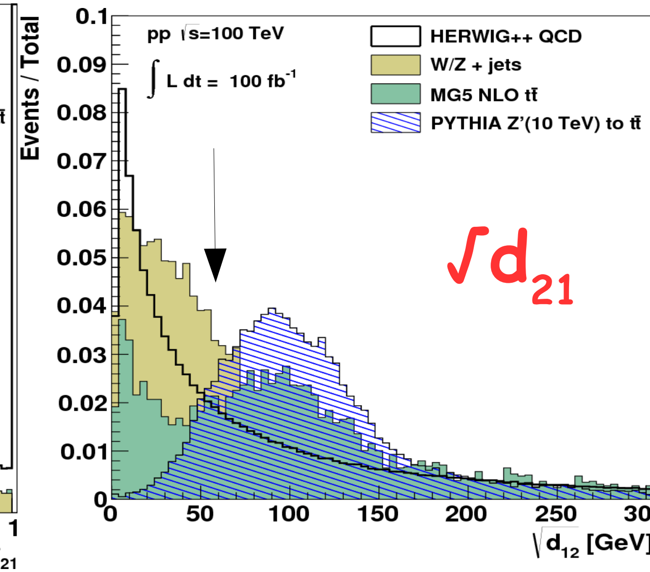
- τ_{32} **>0.75** reduces QCD and boosted W/Z
- τ_{21}**<0.3** reduces W/Z
- τ_{21}**>0.8** reduces QCD background
- $\sqrt{d_{12}}$**> 50 GeV** reduces QCD,W/Z, some $t\bar{t}$

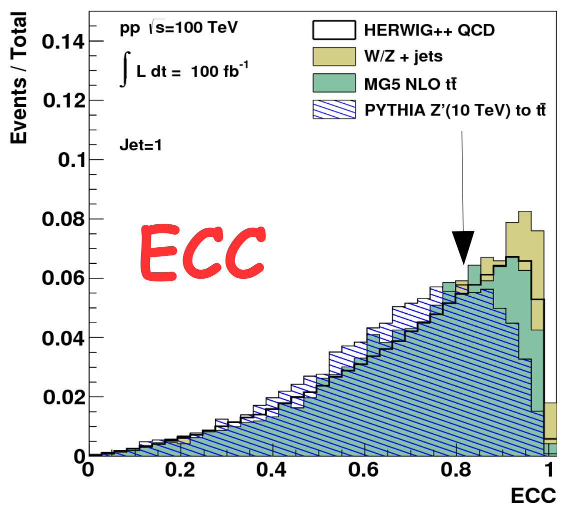
Correlation between variables:
~10% for τ_{32}, τ_{21}, mass
~30% correlation between d_{12} mass, ECC

Discriminating variables (lead. jet) PYTHIA8 → HERWIG++









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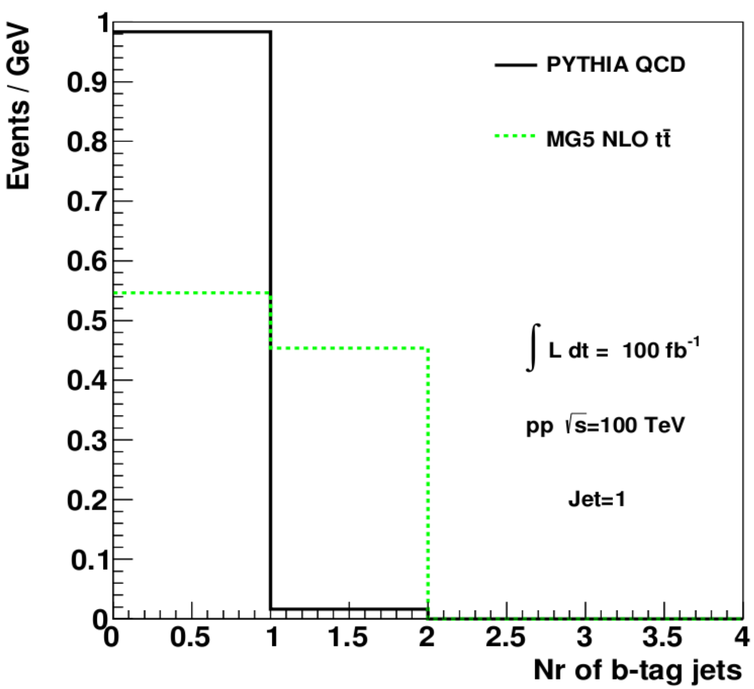
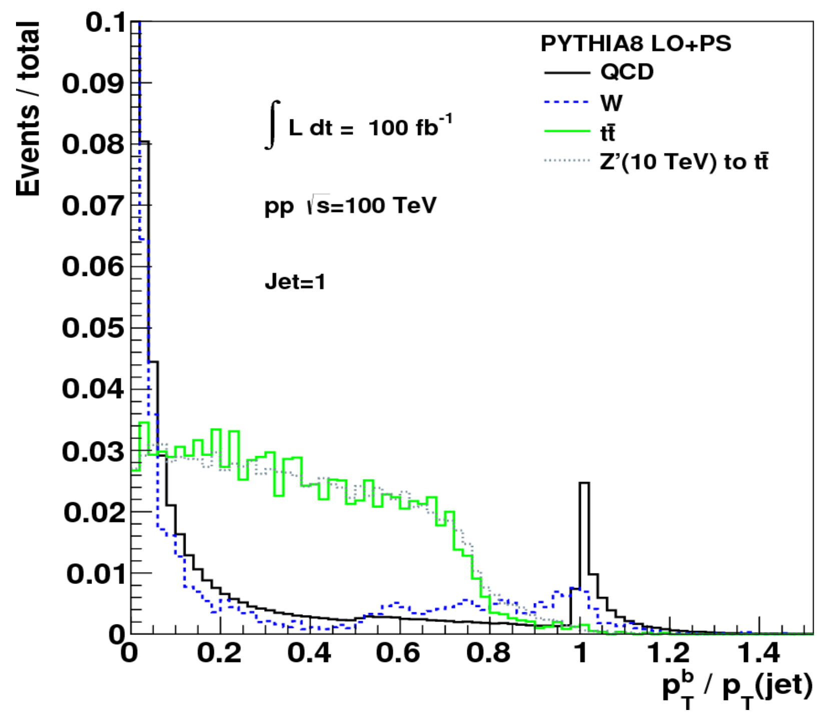
HERWIG++ gives very similar QCD background (contains W/Z brem. events!)

b-tagging and muon pT

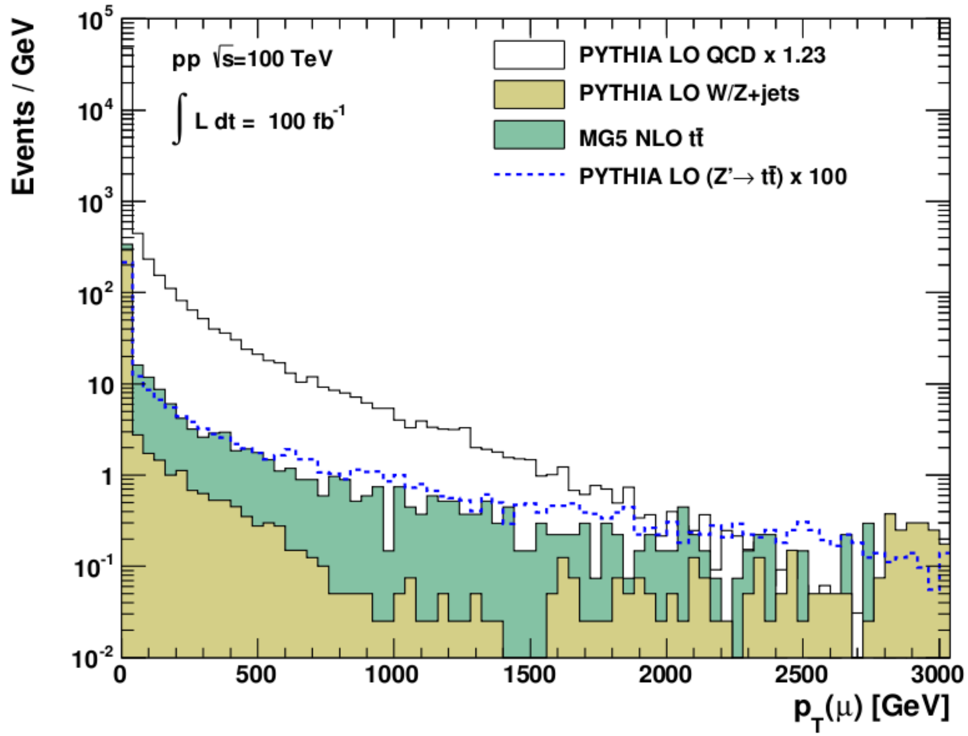
- Match antiKT5 jet with a quark using dR(eta-phi)<0.1
- Assume efficiencies and fake rates:
  - 70% efficiency for b-tagging
  - 10 % fake rate for c-quarks
  - 1% fake rate for light quarks
- b-tagging assumes p_T^b / p_T > 0.2





Muon p_T

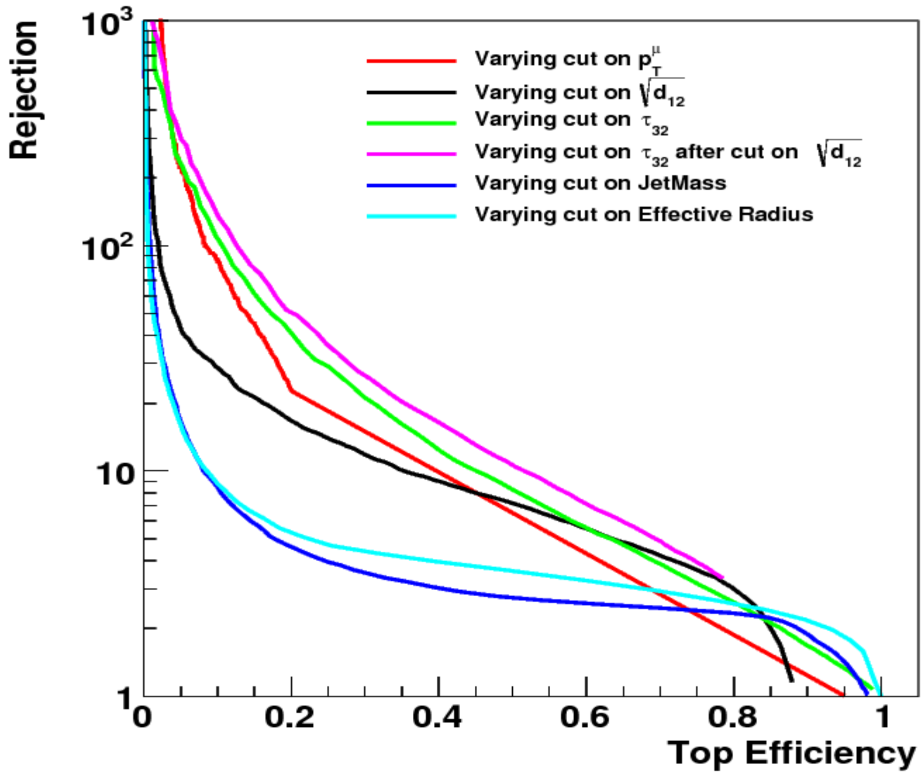
- Can we use muons to reject background?
- We can, but too low statistics for 100 fb^{-1} assuming p_T >1 TeV



What is rejection vs efficiency anyway for all selection variables?

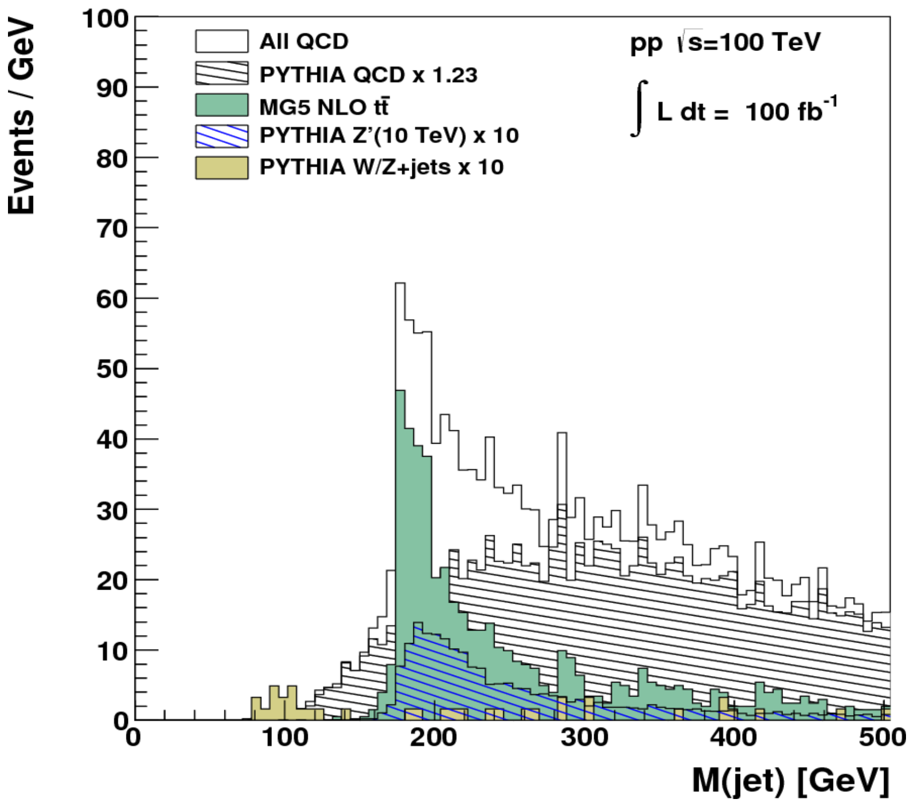
Rejection vs efficiency

- Jet-mass rejection is not attractive option compared to N-subjetiness
  - For the same 50% efficiency τ_{32} has a factor of 3x better rejection than jet mass
- N-subjetiness performs better than a cut on muon



Heavy particles decaying to $t\bar{t}$ at a 100 TeV collider. S.Chekanov et. al (ANL)

Jet mass after selection cuts



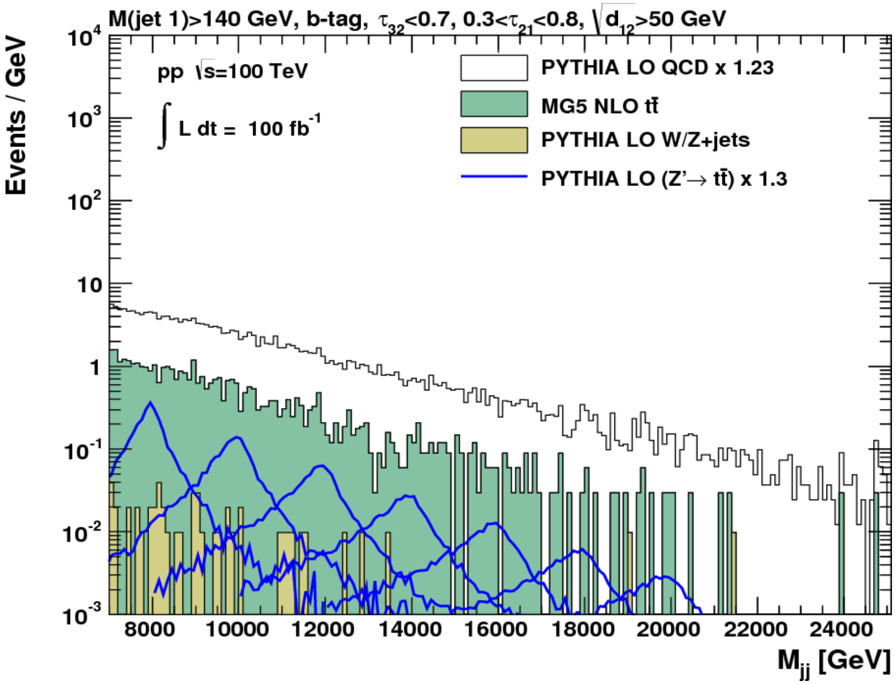
- Consider 2-jet events with pT>2.8 TeV
- "Tag" any jet with the cuts:
  - **b-tagging**
  - **τ_{32}<0.7 and 0.3<τ_{21}<0.8**
  - **$\sqrt{d_{12}}$> 50 GeV**
- Observe a bump in jet mass due to top

100 fb^{-1} should be enough to observe super-boosted single top quarks in fully inclusive channel t+X !
(can be $t\bar{t}$, single top and exotic decays!)

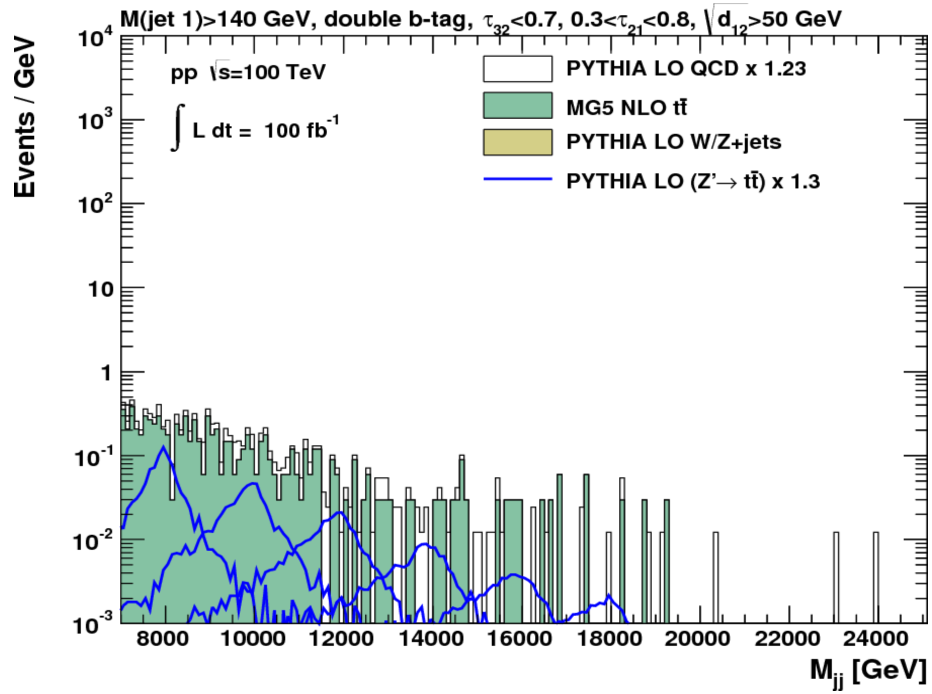
See the 14 TeV case:
B. Auerbach, S. C., N. Kidonakis
arxiv.org:1301.5810 ANL-HEP-13-05. Snowmass

White histogram: all processes (dijet, top, W/Z)

Dijet mass after selection (Z' → $t\bar{t}$)



double b-tag case



- Consider 2-jet events with pT>2.8 TeV
- Apply selection (for any jet):
  - M>140 GeV
  - b-tagging
  - τ_{32}<0.7 and 0.3<τ_{21}<0.8
  - $\sqrt{d_{12}}$ > 50 GeV

before cuts

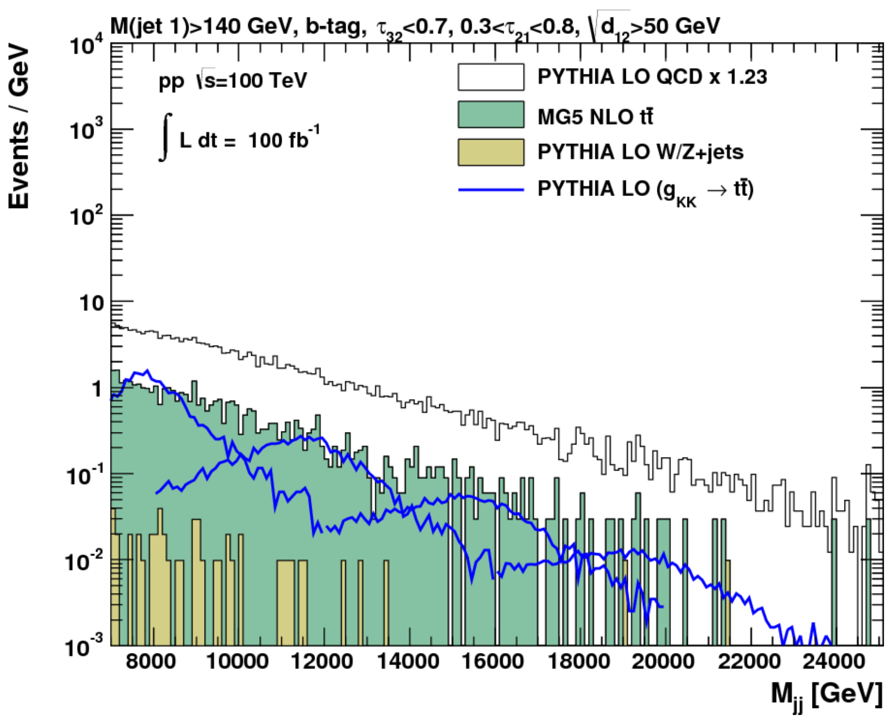
Sig(Z')/Bkg ~ 0.001 → **Sig(Z')/Bkg ~0.03**

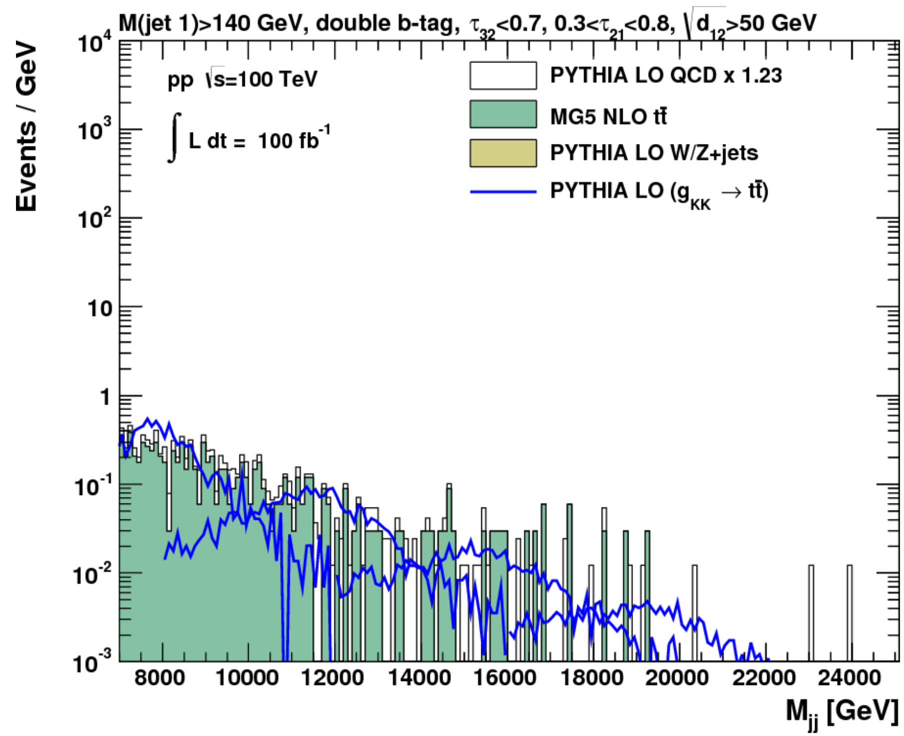
after cuts:
single b-tag +
substructure variables

Not bad!

Dijet mass after selection ($g_{kk} \rightarrow t\bar{t}$)

double b-tag case





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- Apply selection (for any jet):
  - M>140 GeV
  - b-tagging
  - τ_{32}<0.7 and 0.3<τ_{21}<0.8
  - $\sqrt{d_{12}}$ > 50 GeV

after cuts:
single b-tag +
substructure variables

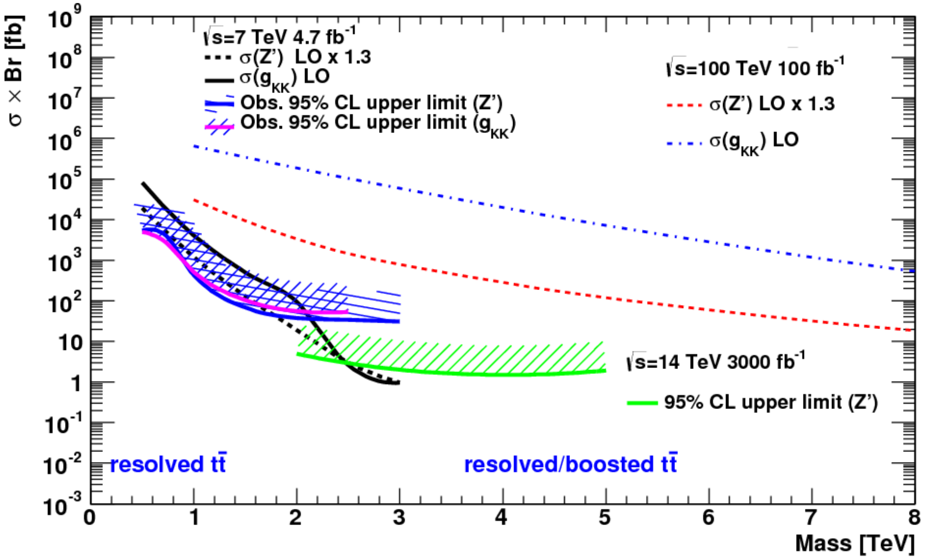
before cuts

Sig(Z')/Bkg ~ 0.002 → **Sig(Z')/Bkg ~0.07**

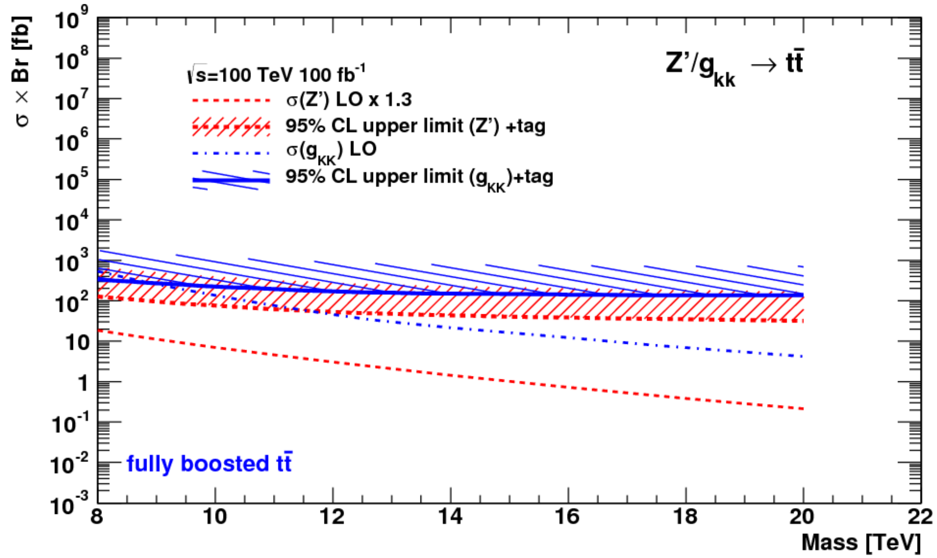
Not bad!

Sensitivity limits for M=0.5-20 TeV

ATLAS, Phys.Rev. D88 (2013) 12004
K.Agashe Snowmass13, arXiv:1309.7847



This study



- **Z'** 95% CL: σxBr ~ 100 fb (M=8 TeV) and 20 fb (M=20 TeV) for 100 fb^{-1}
  - factor ~10 larger compared to predictions. Difficult to observe (low statistics)
  - requires ~500 fb^{-1} for M=10 TeV and ~1000 fb^{-1} for M=20 TeV
- g_{KK} 95% CL: σxBr ~ 600 fb (M=8-20 TeV) for 100 fb^{-1}
  - can be observed assuming LO QCD and $M(g_{KK})$ <10 TeV
  - higher masses require x5 larger luminosity

Summary

- Sensitivity limits on $X \rightarrow t\bar{t}$ calculated in the mass range 8-20 TeV
  - Fully boosted regime (top decays products are not resolved, dijet topology)
  - Technique: b-tagging, substructure variables & jet shapes.
- With the current approach, 100 fb^{-1} is not sufficient to observe Z' / g_{KK} (LO QCD) with masses above 10 TeV. Observation of g_{KK} near 10 TeV is possible
  - Low statistics is the main limitation. Can we further increase S/B ratios?
- Rough projections based on statistical extrapolation of this analysis
  - 100 TeV pp data can be sensitive to:
    - **Z '** : M~15 TeV (5 x100 fb^{-1}) or M~20 TeV (10x100 fb^{-1})
    - **g_{KK}** : M>15 TeV masses require 5x100 fb^{-1}
- Requirements for a future experiment:
  - efficient b-tagging (largest bkg. separation)
  - high-granular calorimeter to apply substructure techniques for R~0.5 jets
  - >500-1000 fb^{-1}
- Paper is in preparation